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OPERATING STRESSES IN AIRCRAFT-ENGINE CRANKSHAFTS AND CONNECTING RODS

II - INSTRUMENTATION AND TEST RESULTS

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WASHINGTON

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

OPERATING STRESSES IN AIRCRAFT-ENGINE CRANKSHAFTS AND CONNECTING RODS

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SUMMARY

An investigation was conducted to develop methods and equipment for the measurement of operating stresses in aircraft-engine crankshafts and connecting rods. Ranges of alternating stress were measured under motoring and power conditions at several locations on the master connecting rod and at one location on the crankshaft of a nine-cylinder radial air-cooled engine modified for test purposes. The results indicate that the measurement of stresses in connecting rods is feasible. Some resonant bending vibration occurred in the rod under all engine operating conditions investigated, but no appreciable resonant axial vibration was found.

INTRODUCTION

At the request of the Air Technical Service Command, Army Air Forces, a program is being carried out at the NACA Cleveland laboratory to develop methods of measuring strains in critical sections of rotating-shaft systems. Several crankshaft failures have been caused by excessive strains due to bending vibration of the crankshaft at its natural frequency. Crankshaft stresses are extremely difficult to determine by analytical methods because many factors, such as natural frequencies, forcing functions, damping capacity, and bearing clearances, are involved and some of these factors cannot be accurately determined. Torsional vibration is commonly measured for experimental analysis of crankshaft stresses; bending vibration of the shaft, however, cannot be determined from torsional-vibration data. Wire strain gages have therefore been used for measurement of bending vibration (reference 1).

No literature on the measurement of operating stresses in connecting rods of high-speed engines has come to the attention of the authors. The importance of investigating vibration conditions in connecting rods has been recognized but, because suitable instrumentation and methods were lacking, experimental strain-measurement investigations have not been made heretofore.

The instrumentation and methods that were used to measure stresses in the crankshaft and the master connecting rod of a modified test engine are described herein and the test results are presented. Wire strain gages were employed for the measurement of dynamic strains in the crankshaft and the master connecting rod. Strain gages mounted and used as described yielded an over-all strain signal of relatively large amplitude, which minimized the effect of distortion caused by slip rings and high-gain amplifiers.

DESCRIPTION OF APPARATUS

Test Engine

The strain-measurement investigation was conducted on an aircraft engine that had been converted to a three-cylinder test engine. The master-rod cylinder (No. 1) was operated under power, whereas cylinders 4 and 7 were motored with exhaust and intake valves installed but with valve push rods removed. The power was absorbed by an electric dynamometer. In all tests, standard laboratory equipment was used to measure engine speed, power output, and cylinder temperatures. The engine was operated with atmospheric inlet pressure inasmuch as supercharging facilities were not available.

Strain Gages and Circuit Diagram

The strain gages used, were attached by means of Bakelite BC-6035 cement. All gages were of 120-ohm nominal resistance with a strain-sensitive area of 1/8 by 1/8 inch square for each gage. The strain was measured by four strain gages, which were mounted on the strained member closely adjacent to each other at the desired locations. (See fig. 1(a).) The strain-sensitive filaments of all four strain gages were orientated in the direction in which it was desired to measure the strain. The filaments of two of the gages were made of Advance wire and those of the other two gages were made of Kovar wire. Advance wire and Kovar wire have strain-sensitivity factors that are opposite in sign and approximately equal in magnitude. The four strain gages were interconnected to form an electrical resistance bridge of the Wheatstone type (fig. 1(b)) with Advance wire gages in two opposite arms of the bridge and Kovar wire gages in the other two opposite arms. The effect of the resistance change of all gages was to change the bridge balance by an amount proportional to the average strain applied to the four strain gages.

The term "strain pickup" is used herein to refer to the combination of four strain gages described in the foregoing paragraph. The effective strain-sensitive area of each strain pickup was 5/16 inch long by 3/8 inch wide.

Crankshaft Strain-Measuring Installation

One strain pickup was located on the propeller side of the front crank arm in the position shown in figure 2. This strain pickup measured the total strain, which consisted of the sum of the alternating strains due to bending and average tension and compression loads in the crank arm. The circuit diagram for this strain pickup is shown in figure 3. The slip rings (fig. 4) were mounted at the outer end of the propeller shaft on the dynamometer coupling flange.

Installation for Measuring Strains in Master Connecting Rod

Six strain pickups were located on the master connecting rod in the positions shown in figure 5. All strain pickups were orientated with strain-sensitive filaments located longitudinally with respect to the connecting rod. The circuit diagram for a typical strain pickup is shown in figure 6. Six slip rings were installed on the master connecting rod (fig. 7). The strain pickups were divided into three groups of two with the battery terminals for each pair connected in parallel. Six slip rings were therefore sufficient to operate one group of strain pickups at a time. The lead wires from the slip rings could be transferred from one group of strain pickups to another by shifting short lead wires on the master connecting rod.

Slip Rings and Brushes

A description of the slip rings and the brushes used in this investigation and their performance characteristics is given in reference 2. The slip-ring and brush contact surfaces were perpendicular to the axis of rotation. The slip rings were made of shim brass 0.016 inch thick with a Vickers hardness number of 150. Silver-graphite brushes 1/8 inch in diameter and 9/16 inch long were used throughout these tests. Four brushes were used for each slip ring with a contact pressure of 250 pounds per square inch for the slip rings mounted on the master connecting rod and for the slip rings fastened to the outer end of the propeller shaft on the dynamometer coupling hub. The slip rings mounted on the connecting rod were operated in oil and the slip rings mounted on the dynamometer coupling hub were operated dry. All slip rings and the brush holders mounted on the crankshaft (fig. 7) were attached with Bakelite BC-6035 cement.

Recording Instruments

The dynamic strains were recorded by a moving-coil type of oscillograph with a galvanometer element having an undamped natural frequency of 2000 cycles per second. The frequency response of the moving-coil type of recording-oscillograph system was found to be constant within ±3 percent from 15 to 500 cycles per second. A moving-coil element with an undamped natural frequency of 500 cycles per second recorded the timing signal, which was obtained from a pickup coil consisting of a few turns of wire wrapped around one of the spark-plug wires.

A cathode-ray oscilloscope in conjunction with a rotating-drum camera was used as a single-channel recording oscillograph to obtain a few strain records for comparison with the records obtained with the moving-coil oscillograph. The frequency response of the cathode-ray oscillograph was found to be constant within ±5 percent from 14 to 2000 cycles per second. Figure 8 shows comparable records obtained with both oscillographs from the same strain pickup under the same engine operating conditions.

TEST PROCEDURE

Strain records were obtained from each of the strain pickups for engine speeds of 1250, 1500, 1750, and 2000 rpm for both motoring and power conditions. All power runs were made at full throttle without boost. Power was determined on an indicated basis by adding the power required to motor the engine to the brake horsepower.

All strain measurements were made with a strain-gage current of 30 milliamperes and with the same amplifier-gain setting. The ordinates of all the oscillograms have the same scale and therefore are directly comparable. The film speed was 10 inches per second for all of the oscillograms except for the record from the cathode-ray oscillograph shown in figure 8, which was 54 inches per second.

The amplifiers and the oscillographs were calibrated by recording the strain signal from a strain pickup mounted at a point of known alternating strain on a vibrating cantilever beam. The same strain-gage current and amplifier-gain setting were used during the calibration as were used during the engine strain-measuring tests. The accuracy of calibrations depends upon the equality of the strain sensitivity of the various strain pickups. The strain sensitivity of a large number of strain gages of the type used in this investigation was measured, and the variation was determined to be not greater than ±1 percent.

RESULTS AND DISCUSSION

Stresses in Crankshaft

The strain in the crank arm at the location shown in figure 2 was measured by strain pickup 1. This pickup was located at a convenient position on the crankshaft to provide a strain signal that would demonstrate the suitability of the instrumentation for measuring dynamic strains in the crankshaft. No attempt was made to locate the strain pickup at the point of maximum stress, inasmuch as development of instrumentation techniques was the prime objective in this preliminary phase of the work. The oscillograms from strain pickup 1 are shown in figure 9. The highest stress range measured at this location for power operation was 12,700 pounds per square inch at speeds of 1500 and 1750 rpm. The maximum stress range when the engine was motored was 5150 pounds per square inch at a speed of 1750 rpm. These stresses were computed from the oscillograms of figure 9 with the assumptions that the strain pickup was orientated in the direction of the major principal axis of strain and that the stress was uniaxial.

Stresses in Master Connecting Rod

Resonant vibrations were found in all the oscillograms (fig. 10) obtained from strain pickup 5, which was located on the flange of the I-beam section of the master connecting rod one-third of the distance from the center line of the master-rod piston-pin bearing to the center line of the master-rod crankshaft bearing. The resonant vibrations were not sustained but varied from a maximum to a minimum amplitude several times throughout the engine cycle. Some of the oscillograms of figure 10 are reproduced to a larger scale in figure 11 to show the wave form more clearly.

Strain pickup 2 was located on the center line of the web of the master connecting rod at the same cross section as pickup 5. This pickup was so close to the neutral axis of the I-beam section that it could not have been greatly affected by bending, and the oscillograms are therefore fairly representative of the average longitudinal strain in the connecting rod at this cross section. Little resonant vibration was obtained from this pickup. (See fig. 12.) It is therefore concluded that the resonant vibration obtained in the records of figure 10 was largely due to bending and that little axial vibration of the master connecting rod occurred.

The range of alternating stress was determined for each strain pickup and test condition by comparing the signals from the strain pickups with the signal from a strain pickup mounted on a calibrator bar subjected to a known uniaxial bending stress. This procedure is based on the assumption that the stress in the connecting rod is uniaxial with the major principal axis along the length of the rod. The results are listed in table I. The maximum range of stress obtained in the master connecting rod for any of the locations and conditions tested was 32,200 pounds per square inch occurring in pickup 6 at an engine speed of 2000 rpm.

The measured range of stress in the master connecting rod as determined from the six strain pickups varied directly with the square of the engine speed (fig. 13) owing to inertia effects when the engine was motored by means of the dynamometer. In the analysis of the oscillograms for inertia stress range at the lower engine speeds, the peak compression-stress amplitude at the time of peak compression pressure and the maximum tensile-stress amplitude that immediately followed were disregarded.

The data presented herein demonstrate that it is practicable to measure dynamic strains in connecting rods. The engine power output could not be extended to high mean effective pressures because boost pressure was not available. No difficulty should be involved with the strain-measuring system if the program is extended to operating conditions at higher engine speeds and mean effective pressures.

SUMMARY OF RESULTS

The results of tests of the dynamic strain-measuring system developed for the R-1820-25 test engine and described herein showed that:

1. Clear and reproducible oscillograms were obtained from strain pickups located on the crankshaft and the master connecting rod.

2. Resonant bending vibrations of the master connecting rod in a plane perpendicular to the crankpin were found to occur in appreciable magnitude for all conditions of engine operation tested.

3. No appreciable resonant axial vibration was found in the master connecting rod.

4. The experimental values of the inertia stress range measured with pickups on the master connecting rod varied directly as the square of the engine speed.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 13, 1945.

REFERENCES

1. Walstrom, Douglas P.: Measurement of Operating Stresses in an Aircraft Engine Crankshaft under Power. NACA ARR No. E5BO1, 1945.

2. Dutee, Francis J., Phillips, Franklyn W., and Kemp, Richard H.: Operating Stresses in Aircraft-Engine Crankshafts and Connecting Rods. I - Slip-Ring and Brush Combinations for Dynamic-Strain Measurements. NACA MR No. E5C30, March 30, 1945.

TABLE I - MASTER-CONNECTING-ROD STRESSES FOR ALL STRAIN-PICKUP LOCATIONS AND ENGINE OPERATING CONDITIONS INVESTIGATED

Strain pickup	Engine speed (rpm)	Indicated mean effective pressure (lb/sq in.)	Range of alternating stress (lb/sq in.)
1	1250	97.2	10,900
	1500	97.6	12,700
	1750	100.7	13,600
	2000	94.5	11,500
2	1250	100.2	23,800
	1500	100.7	24,600
	1750	103.0	24,400
	2000	101.2	25,800
3	1250	96.8	24,000
	1500	98.6	21,400
	1750	99.9	23,800
	2000	91.9	20,500
4	1250	102.5	21,100
	1500	101.1	20,900
	1750	102.5	20,700
	2000	80.5	19,700
5	1250	106.5	29,300
	1500	109.1	30,000
	1750	107.0	29,200
	2000	92.8	27,900
6	1250	103.0	28,900
	1500	107.3	31,100
	1750	107.4	31,500
	2000	96.8	32,200

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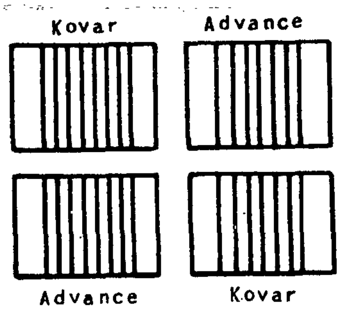
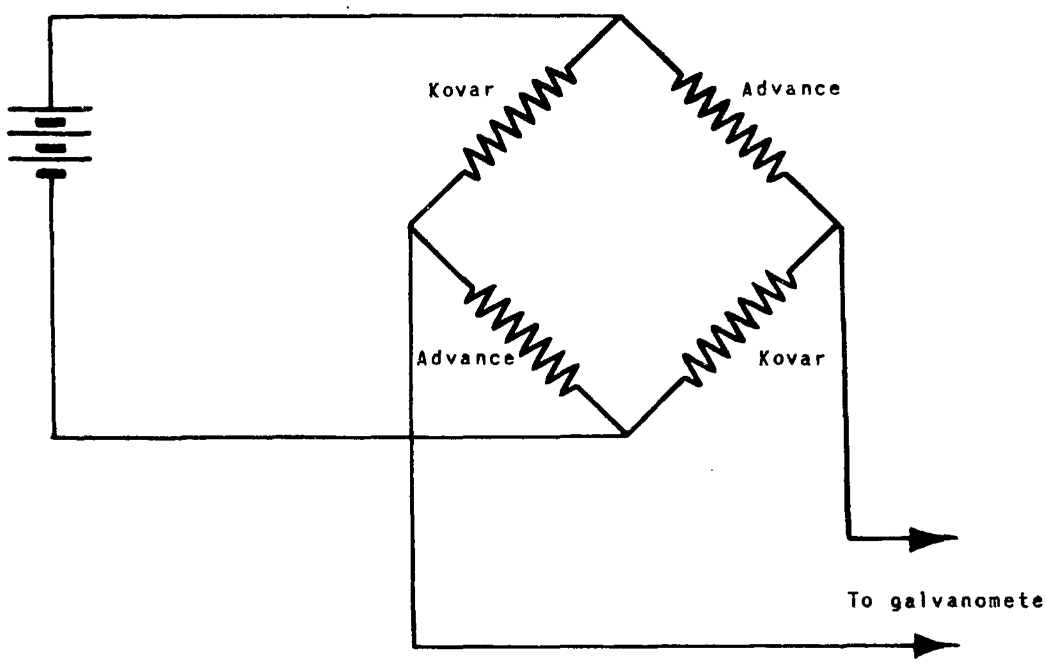


(a) Relative location of four strain gages.



(b) Basic wiring diagram.

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Figure 1. - Strain pickup.

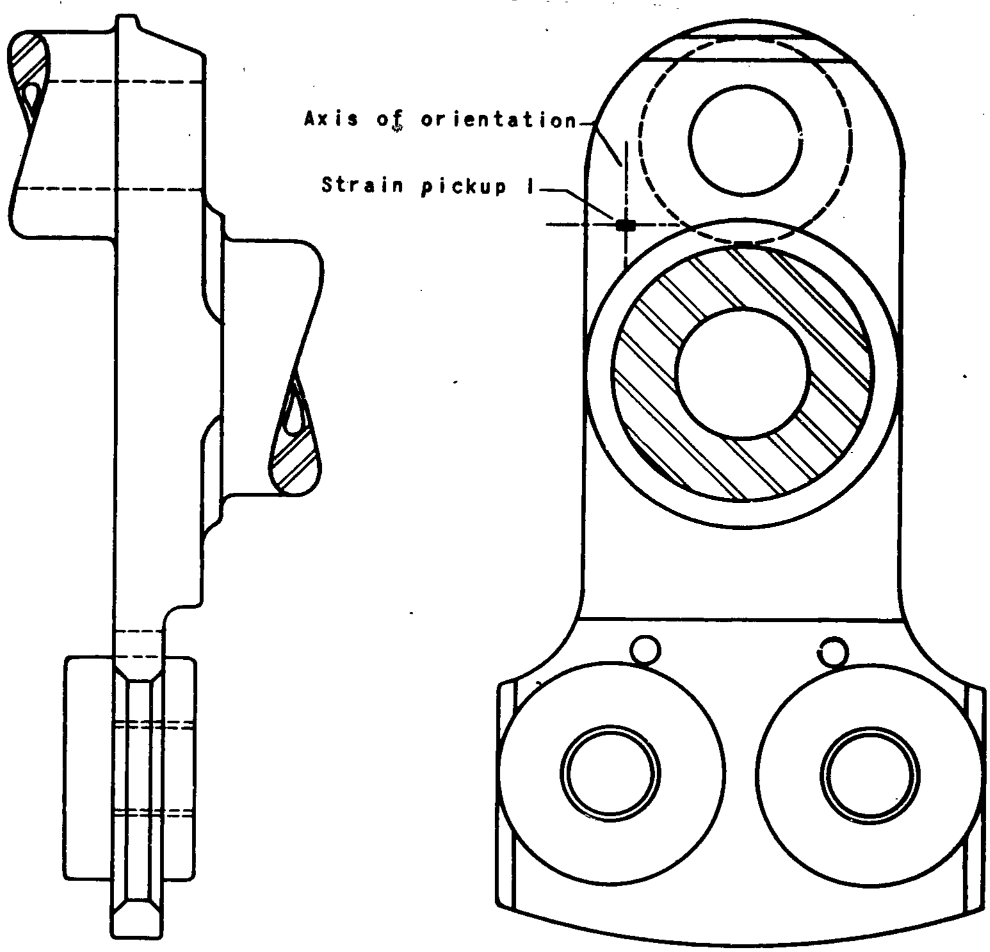

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Figure 2. - Location of strain pickup on propeller side of the front crank arm.

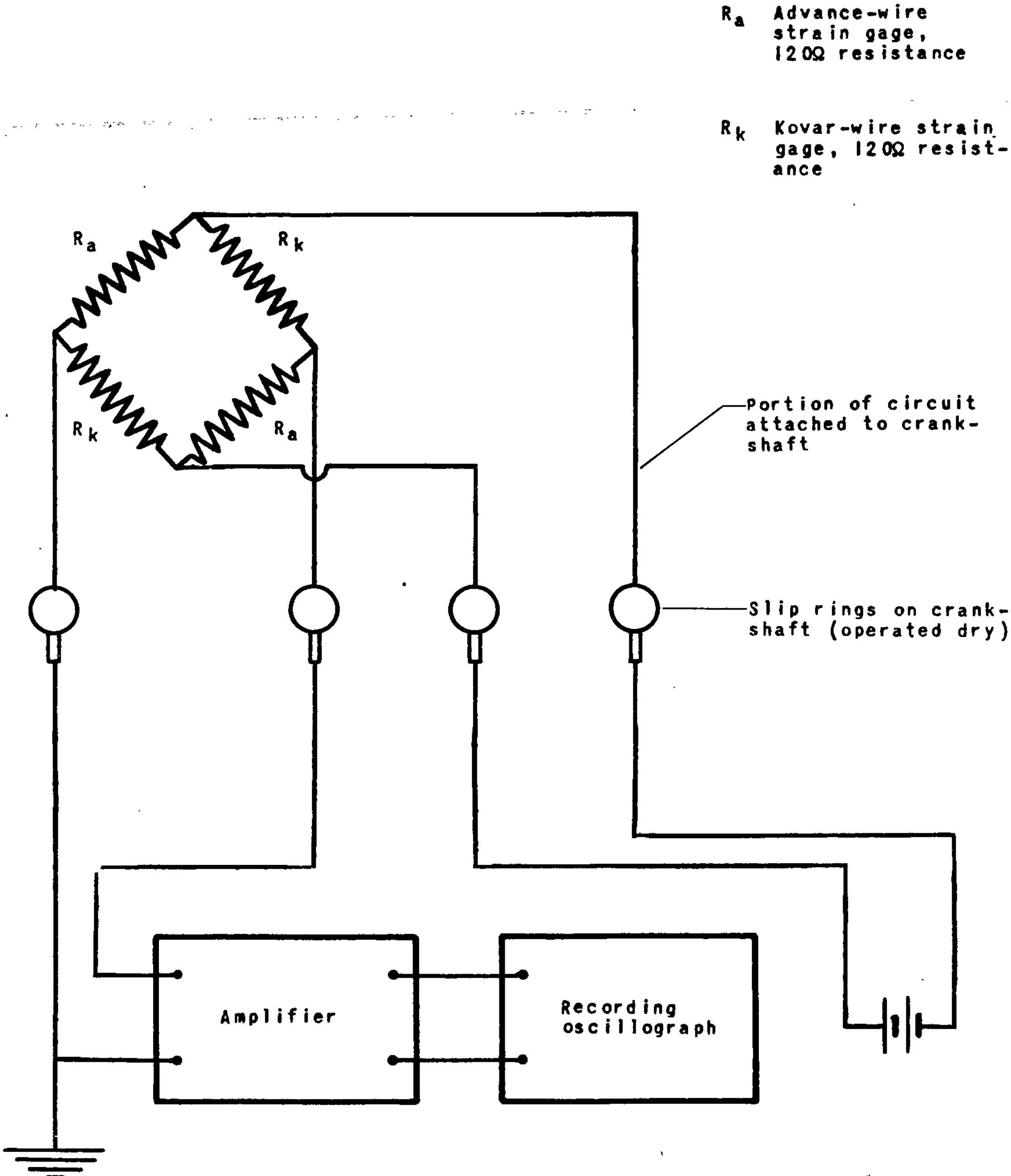

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Figure 3. - Circuit diagram used to measure alternating strain in crankshaft.

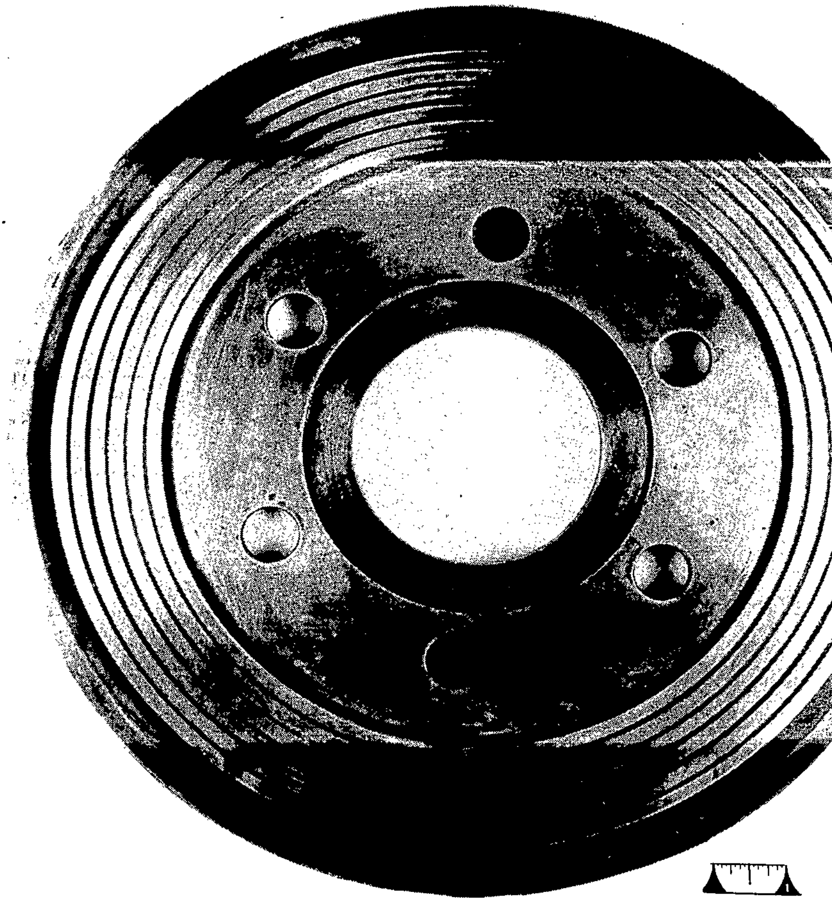

Figure 4. - Slip ring used on crankshaft.

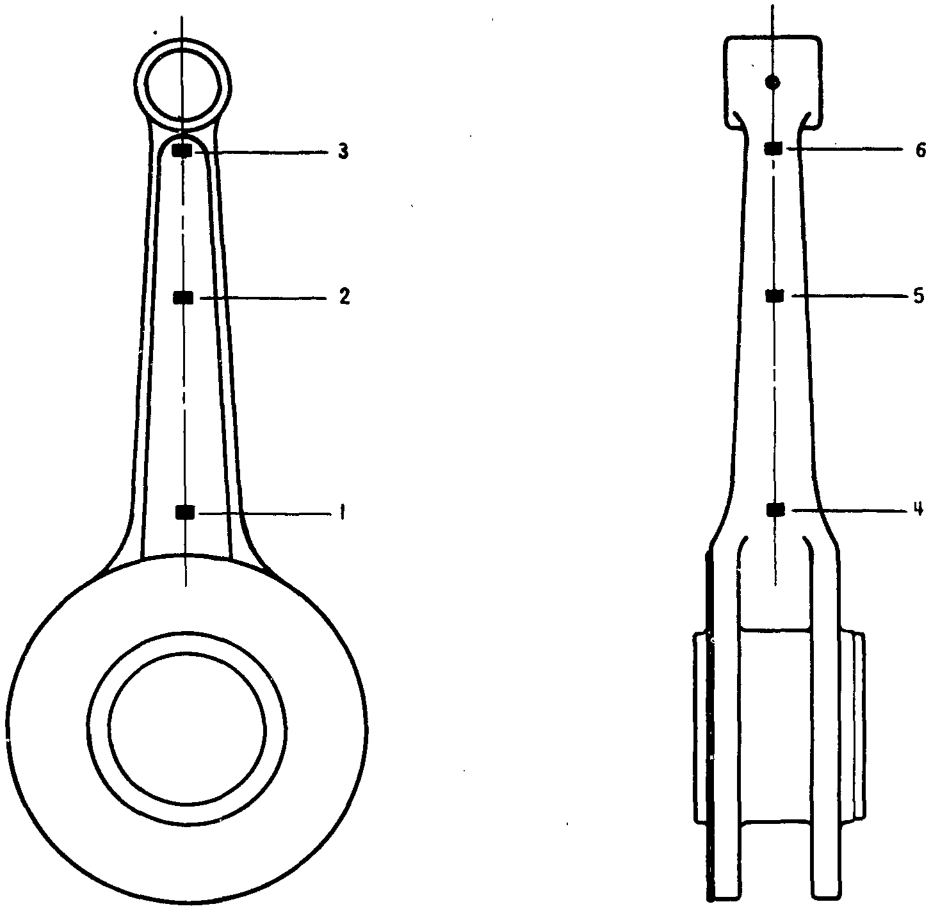

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Figure 5. - Location of strain pickups on antipropeller side of master connecting rod. All pickups have strain-sensitive filaments orientated longitudinally with respect to the rod.

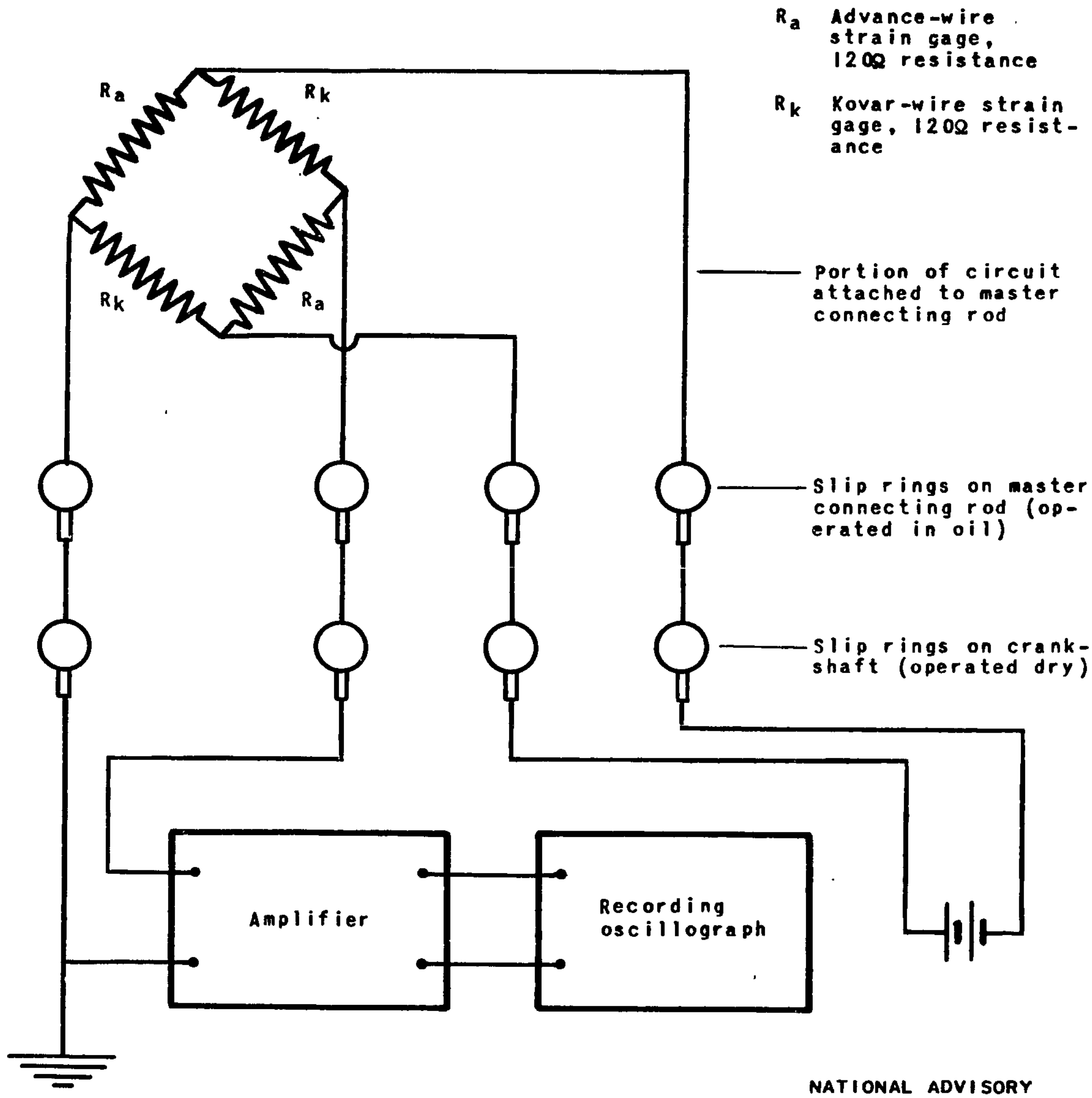

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Figure 6. - Circuit used to measure alternating strain in master connecting rod.

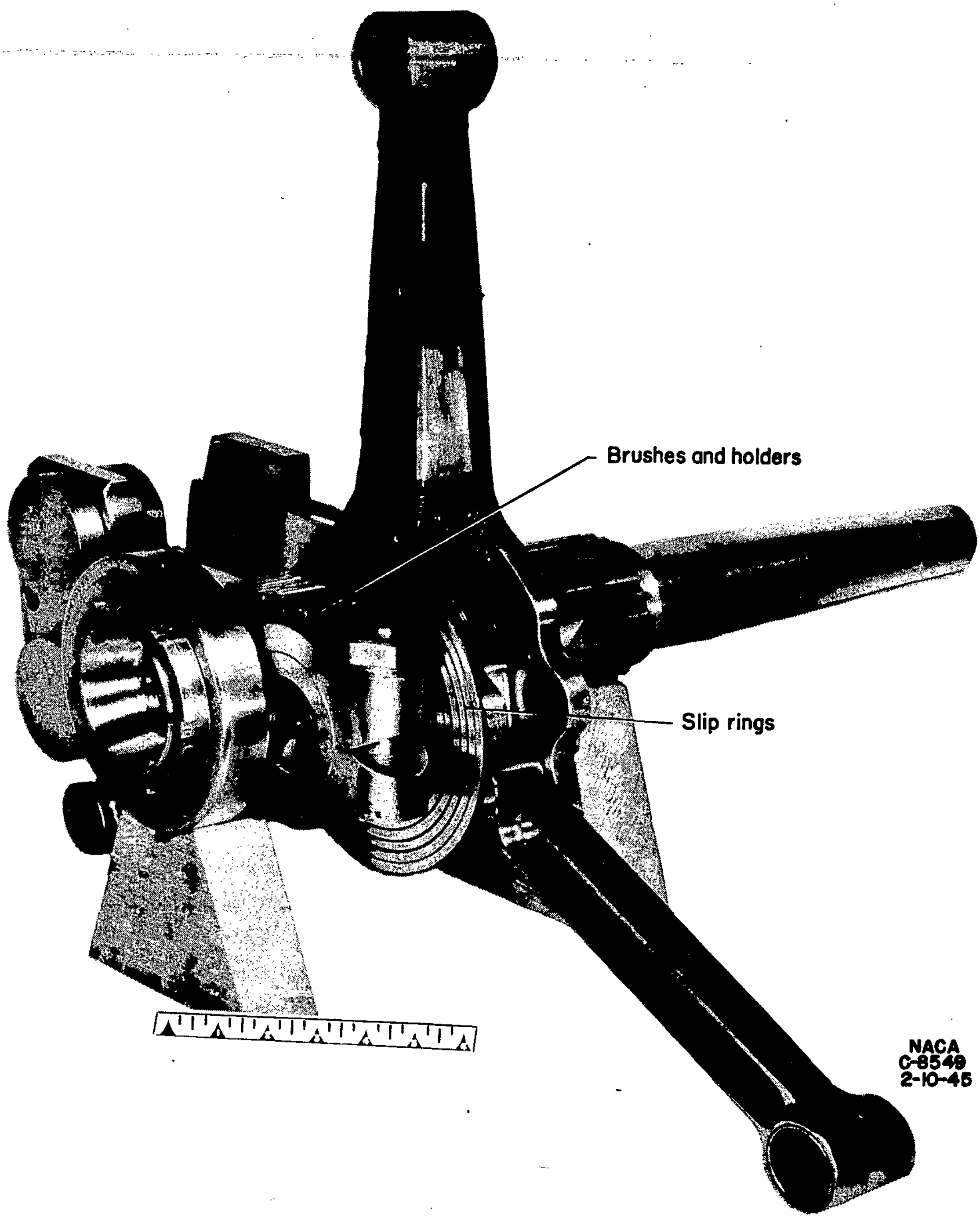
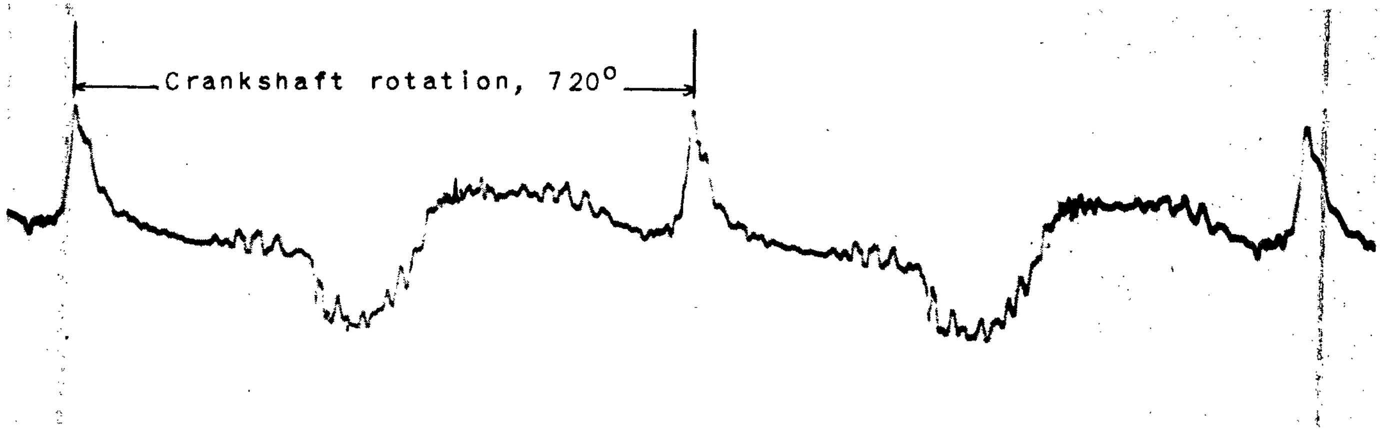
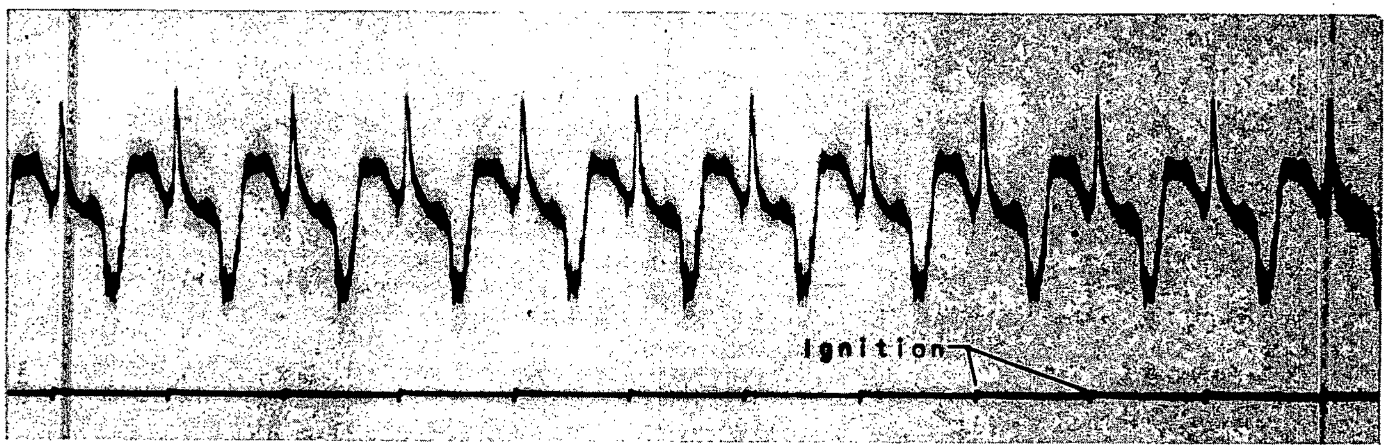


Figure 7. - View of master connecting rod and crankshaft assembly showing strain-measuring installation.



Record from cathode-ray oscillograph



Record from moving-coil oscillograph

Figure 8. - Comparison of records obtained by the moving-coil-type oscillograph and the cathode-ray type of oscillograph

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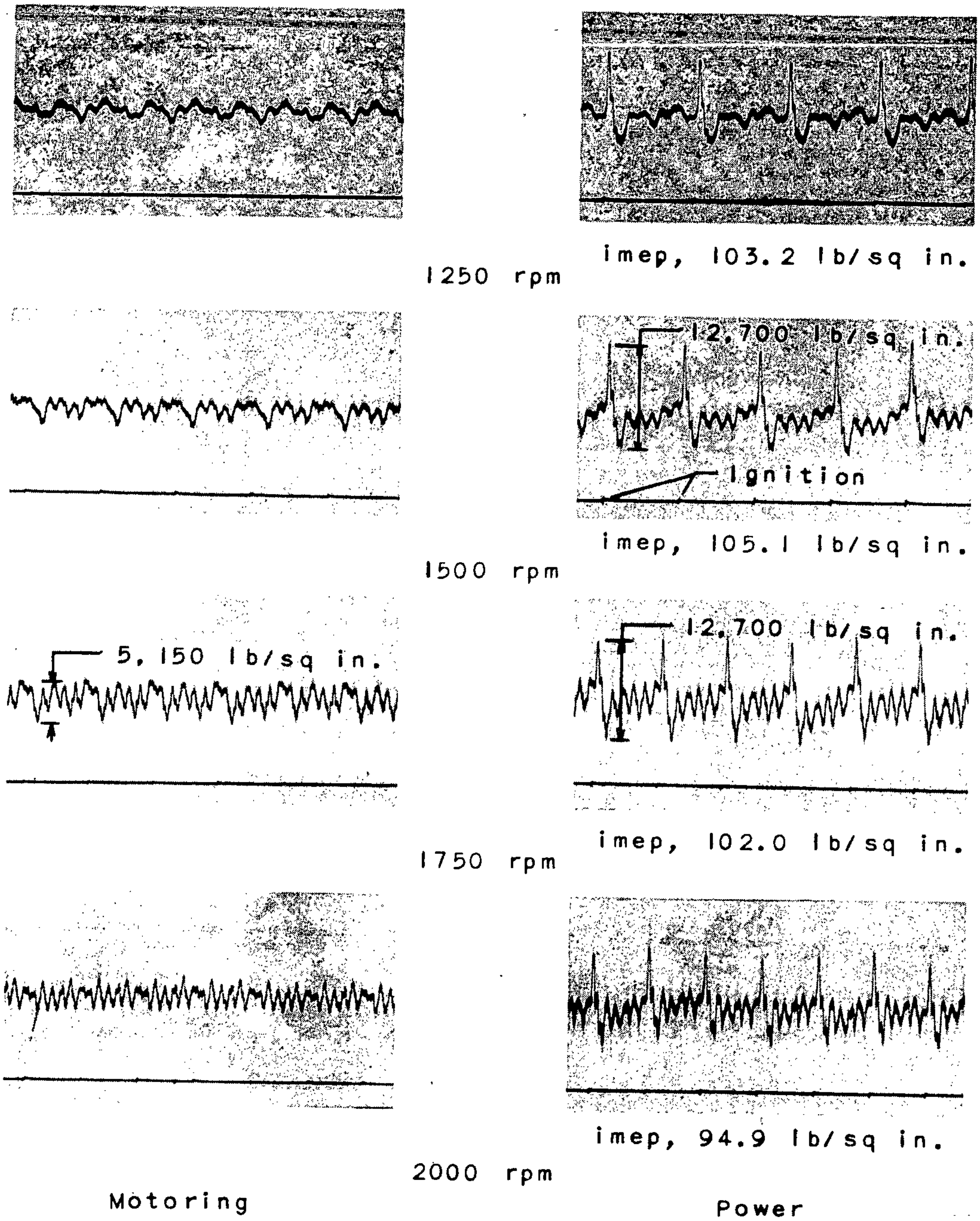

Figure 9. - Oscillograms from strain pickup I on crankshaft for all engine conditions tested. (Reduced to one-half original size.) Ignition timing, 20° B.T.C.

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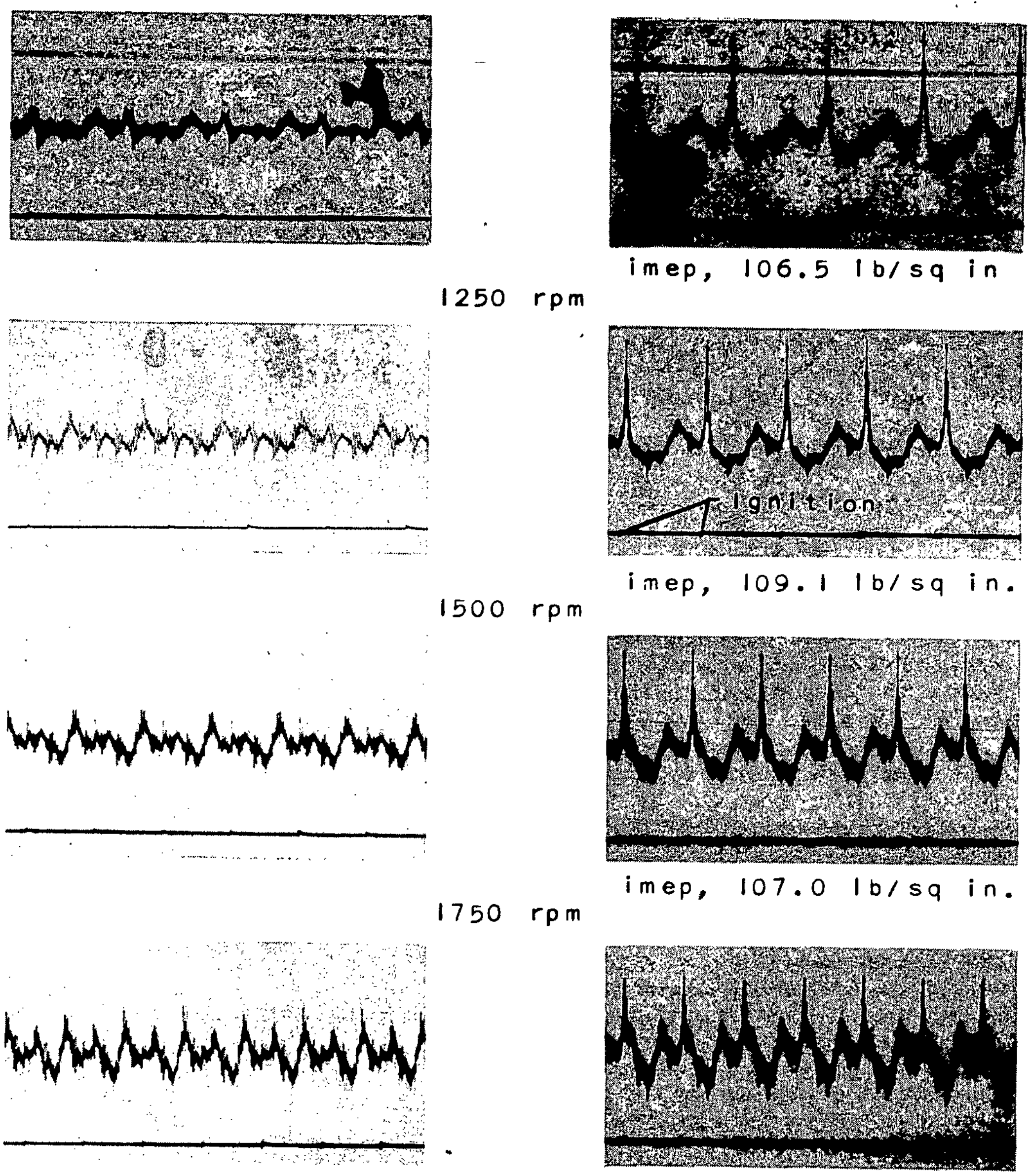

imep, 106.5 lb/sq in

1250 rpm

imep, 109.1 lb/sq in.

1500 rpm

imep, 107.0 lb/sq in.

1750 rpm

imep, 92.8 lb/sq in.

2000 rpm

Motoring

Power

Figure 10. - Oscillograms from strain pickup 5 on master connecting rod for all engine conditions tested. (Reduced to one-half original size.) Ignition timing, 20° B.T.C.

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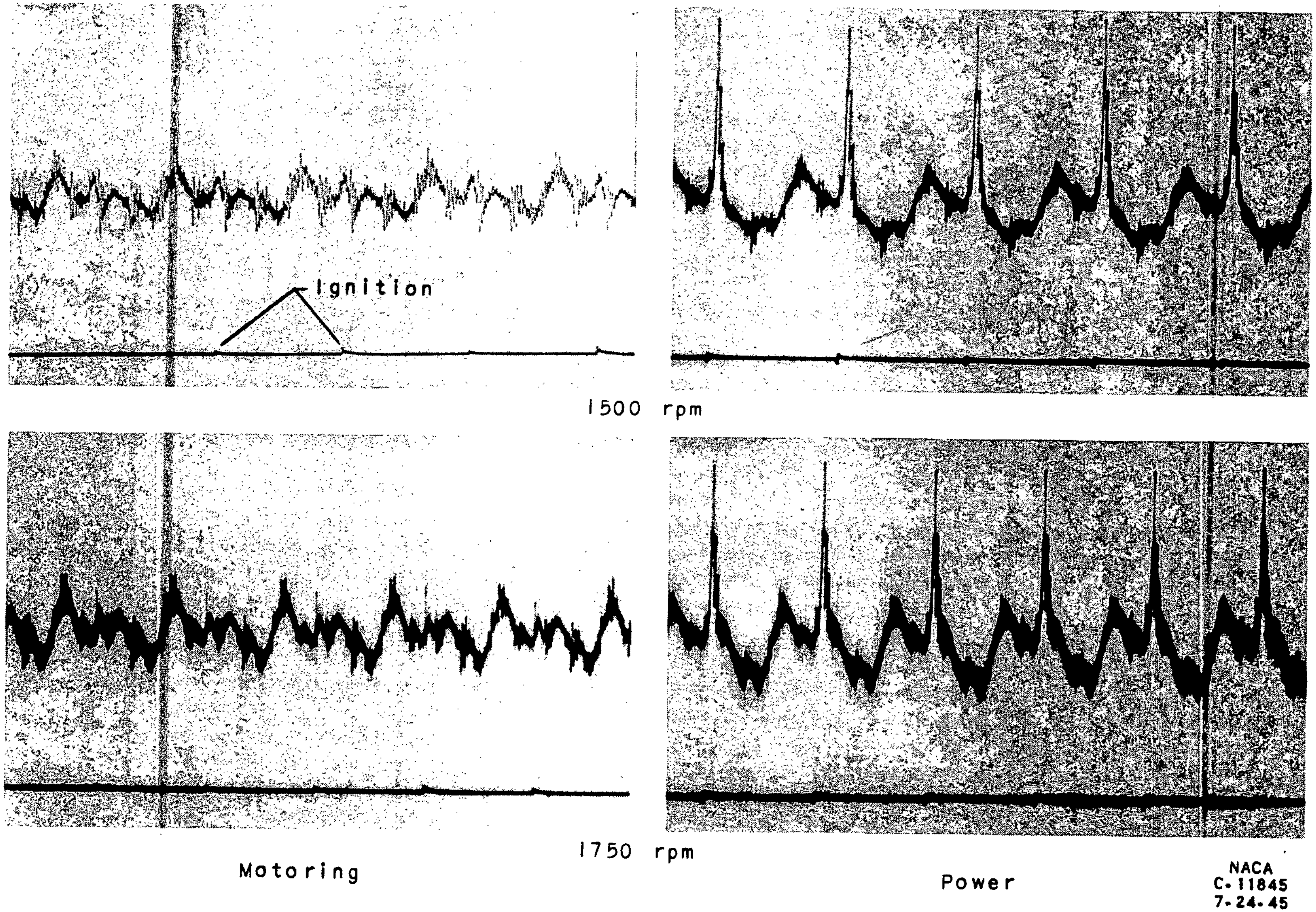

Figure 11. - Oscillograms from strain pickup 5 on master connecting rod for engine speeds of 1500 and 1750 rpm. (Original size.) Ignition timing, 20° B.T.C.

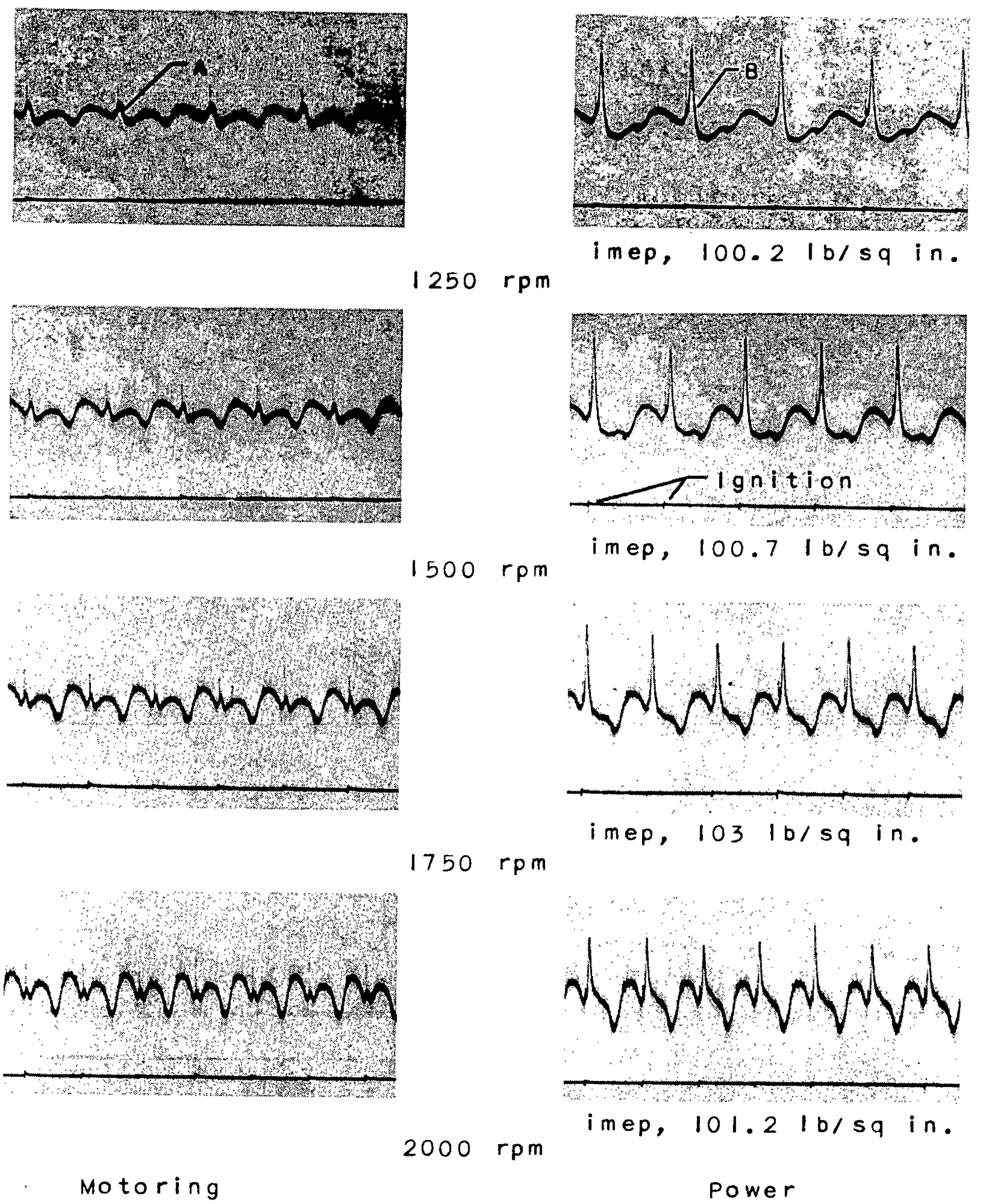

Figure 12. - Oscillograms from strain pickup 2 on master connecting rod for all engine conditions tested. (Reduced to one-half original size.) A, compression pressure peak; B, explosion pressure peak; ignition timing, 20° B.T.C.

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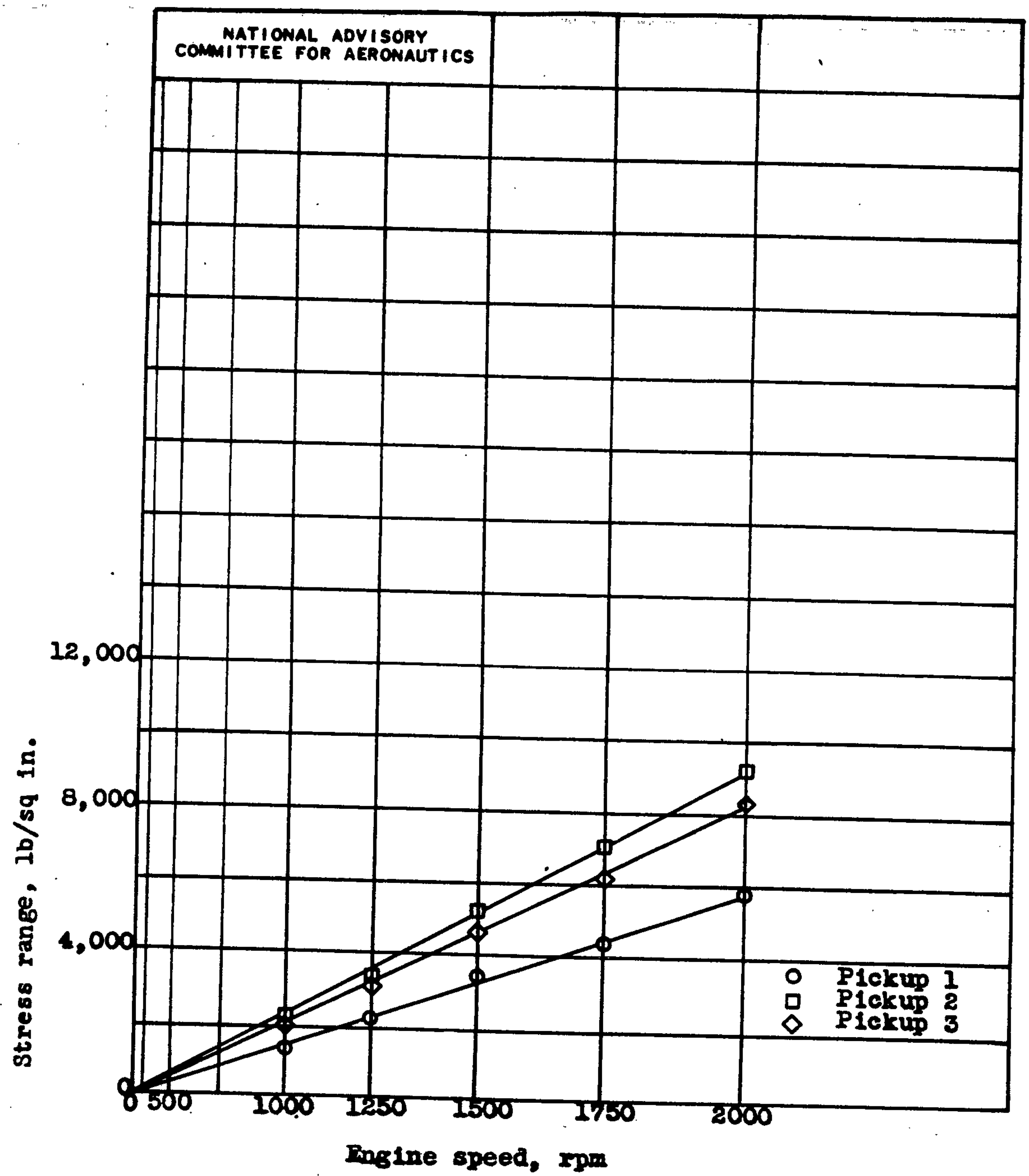

Figure 13. - Effect of engine motoring speed on the range of alternating inertia stress measured in the master connecting rod. Abscissa scale proportional to square of engine speed.

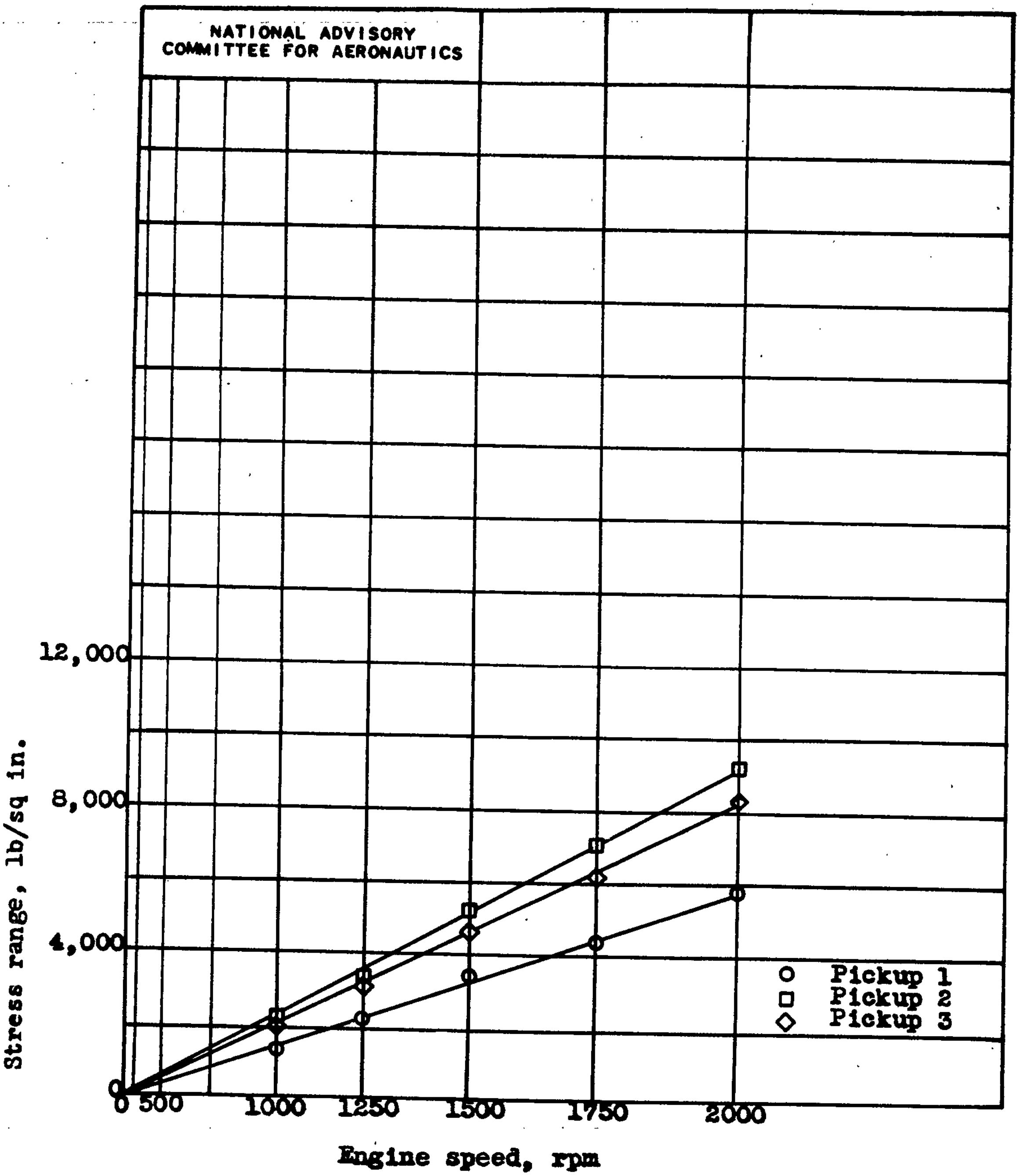

Figure 13. - Effect of engine motoring speed on the range of alternating inertia stress measured in the master connecting rod. Abscissa scale proportional to square of engine speed.